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Original Article

SPECTROSCOPIC DIAGNOSTICS OF HIGH CURRENT DENSITY EXPLODING COPPER WIRE PLASMA ATSTANDARD AMBIENT TEMPERATURE PRESSURE

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ABSTRACT

Optical emission spectroscopy was applied to study electron temperature and electron number densityof plasma generated during exploding copper wires. Neutral spectral lines dominated spectrum in visible range which are used for determination of electron temperature and electron number density. Transitions $3d^9 4s(^3D)5s^2D_{3/2} \rightarrow 3d^9(^2D)4s4p(^3P^0)^2F^0{}_{5/2}$ ***at 464.25 nm,*** $3d^{10}4p^2P^0{}_{3/2} \rightarrow 3d^9 4s^2D_{5/2}$ ***at 510.55 nm,*** $3d^{10}4d^2D_{3/2} \rightarrow 3d^{10}4p^2P^0{}_{1/2}$ ***at 515.32 nm,*** $3d^{10}4d^2D_{5/2} \rightarrow 3d^{10}4p^2P^0{}_{3/2}$ ***at 521.82 nm and*** $3d^{10}4p^2P^0{}_{3/2} \rightarrow 3d^9 4s^{22}D_{3/2}$ ***at 570.02 nm are used for determination of electron temperature using Boltzmann plot method. Electron number density is determined by using Stark broadened 521.82 nm Cu I line. Electron temperature and electron number density is found to be in range 9200 K to 18200 K and*** 3.02×10^{16} ***cm***$^{-3}$ ***to*** 6.91×10^{16} ***cm***$^{-3}$***. Variation of electron temperature and electron number density is studied as function of wire cross section area and discharge energy. Plasma parameters are observed to vary directly with discharge energy and inversely with cross section are of wire being exploded. Validity of assumption of local thmerodynamic equilibrium is also discussed.***

KEYWORDS: Electron Temperature, Electron Number & Local Thmerodynamic Equilibrium

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INTRODUCTION

The phenomena associated with exploding wires are investigated for a variety. Literature is not abundant in its depth but there are a several groupings of papers, theoretical[1-3], purely experimental[4, 5] and combination of these two[6]. It is common to find exploding wire cited for Pressure vessel testing[7], method of propulsion[8], controlled ignition system for solid fuelled ammunitions[9], ignition system for confined fusion research[4], thin film production[10], generation of blast wave[11] and production of high purity metallic and alloy nanoparticles[10, 12].

First observation of exploding wires was reported back to Nairne`s experiment in 1780[13]. During early 20th century research into exploding wires increased due to military interest. It was found that the mechanisms where highly dependent upon local experimental conditions, furthermore slight differences hindered absolute repeatability of the experiments[14]. Crystal size, orientation of metal wire, orientation of cold pre-drawn metal wire, pressure surrounding metal wire, circuit differences and initial temperature differences are the reasons behind

differences in repeated experimentation[15]. Instantaneous current densities during wire explosion depend on type of experimental arrangement and generally are in range of 10^7 to 10^9 A/cm^2 [16-18].Plasma parameters, plasma properties, plume dynamics and effects of laser parameters of laser induced plasmas have been studied extensively using various theoretical models and experiments results [19-23]. Laser induced copper plasma has been extensively studied using Excimer and Nd:YAG lasers[24-26].

Present work reports the study of exploding copper wire plasma in air, carried out by high current density copper wire explosions in air using capacitor bank.Optical emission spectroscopy of exploding wire plasma was recorded to determine electron temperature and electron number density at different discharge energies for wires of different cross sectional area. In our knowledgethis is first report on controlling exploding wire plasma parameters by discharge energy and wire thickness.

EXPERIMENTAL DETAILS

4x4 capacitor bank of total capacitance 10 µF rated at 1800 V was used to give high current density discharge in thin copper wire causing it to explode. Cylindrical copper wires of length 3 cm were exploded for each experiment in a glass tube of typical commercially used electric fuse shape glass cylinder with internal and external diameter of 3 mm and 5 mm respectively. Capacitor bank was constructed by connecting 10 µF, 450 V capacitors with 15mm x 6mm aluminum strips, which was further connected with 3AWG (5.827 mm diameter) copper wire with rated current of 100 A (fuse current of 8.1 kA for 1s and 45 kA for 32 ms) at 38°C. The glass tube was mounted on a fixed stage and radiation from plasma was collected by fiber optics (600 µm core diameter) having a collimating lens with 45° field of view, placed on perpendicular bisector of glass tube at 3.62 cm from glass tube in order to collect all the light produced during explosion. Optical fiber was connected with PC2000 spectrometer (Ocean Optics Inc.) having slit width 25 µm is equipped with 2048 elements CCD array to record optical emission. Spectrum was recorded in range from 350 nm to 850 nm with a resolution of 0.36 nm. Temporal window was set at 100µs delay which was sufficient enough for plasma to be assumed in local thermodynamic equilibrium. Average of five sets of electron temperature and electron number density was taken under same experimental condition.

RESULTS AND DISCUSSIONS

Optical Emission Spectra

Exploding copper wire plasma generated in air by large current pulse expands in a cylindrical pattern away from exploded wire towards inner surface of glass tube due to shockwave [7]. In the present work copper spectra were recorded for different discharge voltage across copper wire from 400 V to 1600 V in 200 V steps having discharge energy ranging from 0.8 J to 12.8 J. Plasma emission was registered as a function of cross-sectional area of exploded wire with diameters 89.7 µm, 127 µm, 160 µm, 227 µm, 286 µm, 321 µm and361 µm. Figure 1 shows the plasma emission spectrum of copper generated by applying 1000 V across 89.7 µm thick copper wire covering range of 350-850 nm. Dominating lines belong to emission of neutral copper, with strongest being observed at 406.24, 464.25, 510.55, 515.32, 521.82, 529.25, 570.02, 578.21, 793.31 and 809.26 nm corresponding to transitions shown in table 1 based on data listed in tables of National Institute of Standards and Technology (NIST)[27].

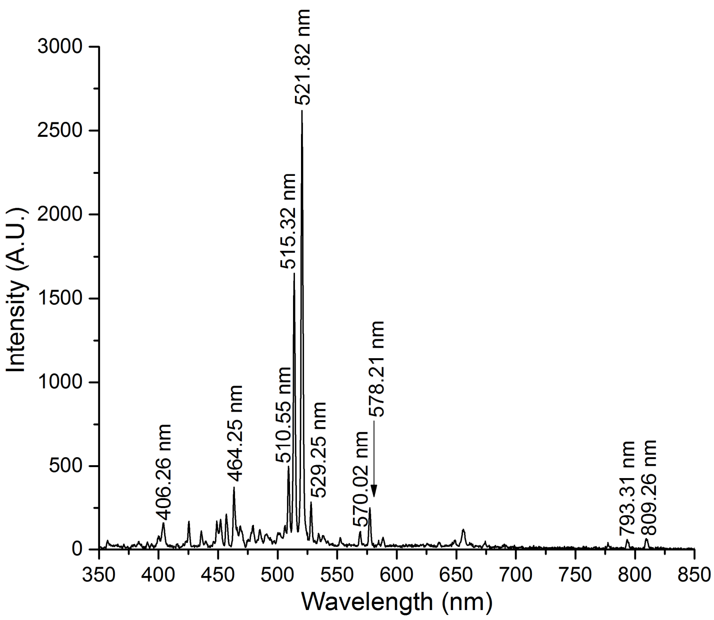

Figure 1: Emission Spectrum of Copper Plasma Generated by Exploding 89.7 µm Diameter Copper Wire at 1000 V Showing Neutral Copper Spectral Lines

Table 1: Spectroscopic Parameters of Cu(I) Lines

Wavelength (nm)	Transitions	Upper Level Statistical Weight (g)	Transition Probabilities ($10^8\ s^{-1}$) (A)	Excitation Energy (eV) (E_n)
406.26	$3d^{10}5d^2D_{5/2}\rightarrow3d^{10}4p^2P^0_{3/2}$	6	1.26	6.94683
464.25	$3d^9\ 4s(^3D)\ 5s\ ^2D_{3/2}\rightarrow3d^9\ (^2D)\ 4s4p(^3P^0)\ ^2F^0_{5/2}$	4	0.074	8.09122
510.55	$3d^{10}\ 4p\ ^2P^0_{3/2}\rightarrow3d^9\ 4s\ ^2D_{5/2}$	4	0.02	3.81669
515.32	$3d^{10}\ 4d\ ^2D_{3/2}\rightarrow3d^{10}\ 4p\ ^2P^0_{1/2}$	4	0.6	6.19117
521.82	$3d^{10}\ 4d\ ^2D_{5/2}\rightarrow3d^{10}\ 4p\ ^2P^0_{3/2}$	6	0.75	6.19203
529.25	$3d^94s(^3D)5s^4D_{7/2}\rightarrow3d^9(^2D)4s4p(^3P^0)^4D^0_{7/2}$	8	0.109	7.73703
570.02	$3d^{10}\ 4p\ ^2P^0_{3/2}\rightarrow3d^9\ 4s^{2}\ ^2D_{3/2}$	4	0.0028	3.81669
578.21	$3d^{10}4p^2P^0_{1/2}\rightarrow3d^94s^{22}D_{3/2}$	4	0.0028	3.81669
793.31	$3d^{10}5s^2S_{1/2}\rightarrow3d^{10}4p^2P^0_{1/2}$	2	-[a]	5.34833
809.26	$3d^{10}5s^2S_{1/2}\rightarrow3d^{10}4p^2P^0_{3/2}$	2	-[a]	5.34833

[a] Transition probabilities not yet reported in literature

Electron Temperature

Electron temperature was determined using Boltzmann plot method by assuming the plasma in local thermodynamic equilibrium (LTE) [28-30] using:

$$ln\left(\frac{I_{nk}\lambda_{nk}}{A_{nk}g_n}\right)_i = a - \frac{E_i}{kT} \tag{1}$$

where I_{nk} isintegrated line intensity of transition involving upper level (*n*) to lower level (*k*), λ_{nk} is wavelength associated with the transition, A_{nk} is the transition probability, $g_n$is upper level (n) statistical weight, E_n is energy of upper level (*n*), *a* is ratio of total number density and partition function which remains constant, *k* is Boltzmann constant and *T* is excitation temperature. Boltzmann plot between *ln(Iλ/gA)* and upper level energy E_n whose slope equals (*-1/kT*) gives electron temperature. Error originating from uncertainty in transition probabilities and integrated intensities is determined to be ≈10%. Line identification and different spectroscopic parameters such as wavelength(*λ*), transition levels, transition

probabilities (*A*), statistical weight (*g*) and upper level energy listed in table 1 are taken from NIST atomic spectroscopy database[27]. For determination of electron temperature neutral copper lines at 464.25 nm, 510.55 nm, 515.32 nm, 521.82 nm and 570.02 nm were used.

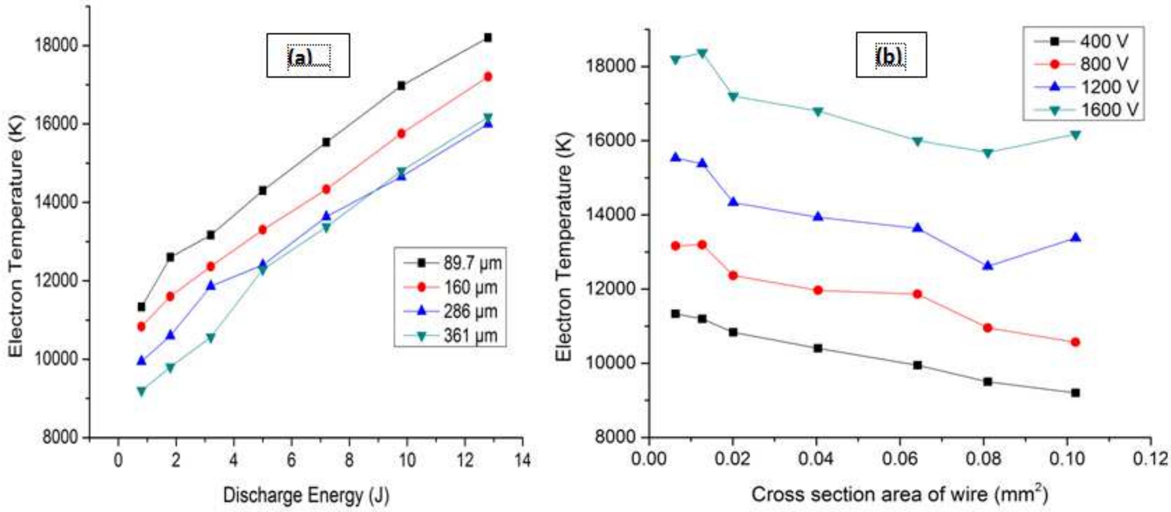

Figure 2: (a)Variation of Electron Temperature with Discharge Energy for Explosion for Wires of Diameter 89.7 µm, 160 µm, 286 µm and 361 µm. (b) Variation of Electron Temperature with Cross Sectional Area of Wire at 400, 800, 1200 and 1600 V

Behavior of electron temperature was studied as function of energy provided for wire explosion and thickness of wire being exploded. It was observed that electron temperature varied from 9893 K to 17205 K for 400 to 1600 volts with 0.8 J to 12.8 J discharge energy for 160 µm diameter wires, same experiment was repeated for wires of diameter 89.7 µm, 127 µm, 227 µm, 286 µm, 321 µm and 361 µm. Behaviorof electron temperature with applied voltage and discharge energy at wires of diameter 89.7 µm, 160 µm, 286 µmand 361 µm is shown in Figure 2(a). It is evident that electron temperature increases with applied voltage which obviously is due to increase in discharge energy provided by capacitor bank. Behavior of electron temperature varies as square of the applied voltage and almost linearly with the discharge energy. It can also be seen that electron temperature drops as the wire thickness increases. Figure 2(b) shows the behavior of electron temperature with cross sectional area of the wire at 400 V, 800 V, 1200 V and 1600 V, which clearly indicates that electron temperature decreases almost linearly by increasing cross sectional area of wire being exploded which indicates direct dependence of electron temperature on current density in the wire during explosion.

Electron Number Density

Main sources of line broadening are Doppler broadening, ion-impact broadening and Stark broadening. Since the plasma is initially in free expansion state [31], contribution of ion-impact broadening is neglected. The estimated Doppler's width for Cu (I) line at 521.2 nm is 0.00297 nm, corresponding to a 10000 K plasma temperature, and observed line width is around 1.8 nm. Since Doppler broadening contribution is negligibly smaller than observed line width, major contribution is attributed to Stark broadening. Electron number density (N_e) related to full width at half maximum (FWHM) of Stark broadened lines is given by the estimation of the FWHM ($\Delta\lambda_{1/2}$) for neutral atoms as[32-34]:

$$\Delta\lambda_{1/2} = 2\omega\left(\frac{N_e}{10^{16}}\right) + 3.5A\left(\frac{N_e}{10^{16}}\right)^{1/4}\left[1-\frac{3}{4}N_d^{-1/3}\right]\left(\frac{N_e}{10^{16}}\right) \quad \ldots \quad (2)$$

Where ω represents electron impact width parameter, A is ion broadening parameter,N_e is electron number density and N_d is number of particles in Debye sphere. First term refers to broadening due to the electron contribution, whereas second term is attributed to ion broadening. Since contribution of ionic broadening is usually very small, it can be neglected [35, 36] and above equation reduces to a simpler form:

$$\Delta\lambda_{1/2} = 2\omega\left(\frac{N_e}{10^{16}}\right) \quad \ldots \qquad (3)$$

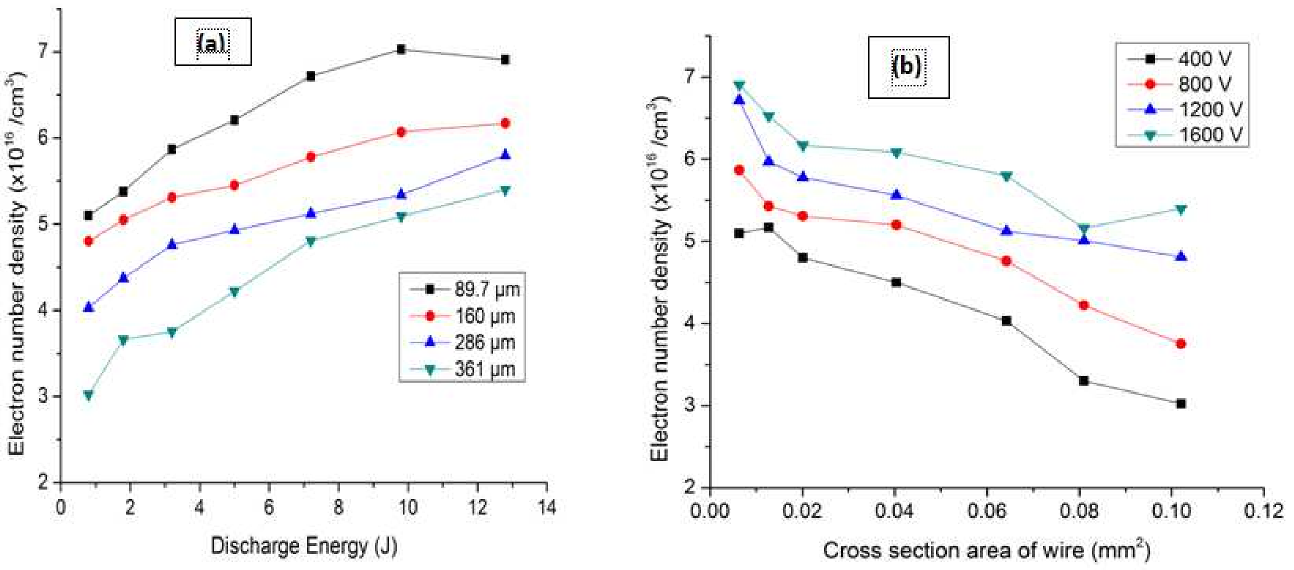

Figure 3: (a)Variation of Electron Number Density with Discharge Energy for Explosion for Wires of Diameter 89.7 µm, 160 µm, 286 µm and 361 µm, (b) Variation of Electron Number Density with Cross Sectional Area of Wire at 400, 800, 1200 and 1600 V

Electron number density of the plasma was determined by using strongest observed neutral copper line at 521.82 nm fitted with Voight profile, value of electron impact width parameter corresponding to different plasma temperatures is taken from the reference data tabulated by Konjevic and Wiese[37].

The behavior of electron number density was studied as a function of discharge energy provided for wire explosion and cross sectional area of wire being exploded. It was observed that electron number density varied from 4.8×10^{16}cm^{-3} to 6.17×10^{16} cm^{-3} for 400 to 1600 volts having discharge energy from 0.8 to 12.8 J for 160 µm diameter copper wire. Same experiment was repeated for wires of diameter 89.7 µm, 127 µm, 227 µm, 286 µm, 321 µm and 361 µm. Behavior of electron number density with discharge energy at wires of diameter 89.7 µm, 160 µm, 286 µmand 361 µm is shown in figure 3(a). It is evident that electron number density increases with increase in discharge energy provided by the capacitor bank. Figure 3(b) shows the behavior of electron number density with cross sectional area of the wire at 400 V, 800 V, 1200 V and 1600 V, which clearly indicates that electron number density decreases by increasing the cross sectional area of wire being exploded showing direct dependence of electron number density on current density in the wire during explosion.

Validity of Assumption of Local Thermodynamic Equilibrium

Optically thick plasmas do not give meaningful values of the plasma parameters, for determination of electron temperature and electron number density optically thin plasma is necessary. During the early stages of explosion, plasma is

observed to be optically thin. Optically thick plasmas would have self-absorption where strong lines would have dips at the central wavelengths, however in spectra used for present calculations, no dips at central wavelength of observed lines were found. The condition of LTE that the atomic and ionic states should be populated and depopulated predominantly by electron collisions, rather than by radiation, requires an electron density which is sufficient to ensure the high collision rate. Validity of the assumption of LTE is confirmed by McWhirter's criterion [38, 39], which conditions the minimum electron number density.

$$N_e \geq 1.6 \times 10^{12} T^{1/2} \Delta E^3 \qquad \ldots \qquad (4)$$

Where T (K) is the plasma temperature and ΔE (eV) is the energy difference between the states which are expected to be in local thermodynamic equilibrium (LTE). At temperature 14000 K and states corresponding to copper line at 521.82 nm, equation (4) yields $N_e \approx 2\times10^{15}$ cm^{-3}, which defines the validity of LTE plasma in the present work.

CONCLUSIONS

We have studied exploding copper wires for plasma parameters. Emission spectrum in visible region shows transition of neutral copper in plasma. Electron temperature and electron number density has been determined as a function of discharge energy and cross section area of the wire being exploded. It was observed that the electron temperature and electron number density increases with discharge energy and vice versa. Variation of electron temperature and electron number density with diameter of wire being exploded shows the direct relation of these parameters with the current density in the wire as both decrease with increasing cross section area of wire. Plasma parameters reported in this work are of same order of magnitude as previously reported in literature for other plasma generation techniques[19, 24, 26]. We show that plasma parameters can be controlled with good accuracy by variation of discharge energy and cross sectional area of wire being exploded.

REFERENCES

1. *Lukyanov, A. and S. Molokov, Flexural magneto-elastic vibrations of thin metal wires. Journal of Physics D: Applied Physics, 2004.* ***37****(5): p. 784.*
2. *Lukyanov, A. and S. Molokov, Flexural vibrations induced in thin metal wires carrying high currents. Journal of Physics D: Applied Physics, 2001.* ***34****(10): p. 1543.*
3. *Molokov, S. and J. Allen, The fragmentation of wires carrying electric current. Journal of Physics D: Applied Physics, 1997.* ***30****(22): p. 3131.*
4. *Hammer, D. and D. Sinars, Single-wire explosion experiments relevant to the initial stages of wire array z pinches. Laser and Particle Beams, 2001.* ***19****(03): p. 377-391.*
5. *Graneau, P., Longitudinal magnet forces? Journal of Applied Physics, 1984.* ***55****(6): p. 2598-2600.*
6. *Hollandsworth, C.E., et al., Electrical conduction in exploded segmented wires. Journal of applied physics, 1998.* ***84****(9): p. 4992-5000.*
7. *Zhang, C., J. Yang, and X. Chi, Research on plasma explosion of metal wire in water, in Electrical Insulation, 2004. Conference Record of the 2004 IEEE International Symposium on. 2004. p. 257-260.*
8. *Keidar, M., I. Beilis, and others, Vacuum arc plasma jets and their applications, in Plasma Science, 2003. ICOPS 2003. IEEE Conference Record-Abstracts. The 30th International Conference on. 2003. p. 138.*

9. *Taylor, M.J., Formation of plasma around wire fragments created by electrically exploded copper wire. Journal of Physics D: Applied Physics, 2002.* ***35****(7): p. 700.*

10. *Sen, P., et al., Preparation of Cu, Ag, Fe and Al nanoparticles by the exploding wire technique. Journal of Chemical Sciences, 2003.* ***115****(5-6): p. 499-508.*

11. *Liverts, M., et al., Mitigation of exploding-wire-generated blast-waves by aqueous foam. Physics of Fluids, 2015.* ***27****(7): p. 076103.*

12. *Alqudami, A., et al., Ag-Au alloy nanoparticles prepared by electro-exploding wire technique. Journal of Nanoparticle Research, 2008.* ***10****(6): p. 1027-1036.*

13. *Nairne, E., An Account of the Effect of Electricity in Shortening Wires. By Mr. Edward Nairne, FRS. Philosophical Transactions of the Royal Society of London, 1780.* ***70****: p. 334-337.*

14. *Williams George Chace, H.K.M., Exploding wires. Vol. 1. 1959: Plenum Press: Chapman & Hall.*

15. *Bennett, F.D., H.S. Burden, and D.D. Shear, Expansion of superheated metals. Journal of Applied Physics, 1974.* ***45****(8): p. 3429-3438.*

16. *Sedoi, V.S., et al., The current density and the specific energy input in fast electrical explosion. Plasma Science, IEEE Transactions on, 1999.* ***27****(4): p. 845-850.*

17. *Tucker, T., Behavior of exploding gold wires. Journal of Applied Physics, 1961.* ***32****(10): p. 1894-1900.*

18. *Pikuz, S., et al., Multiphase foamlike structure of exploding wire cores. Physical review letters, 1999.* ***83****(21): p. 4313.*

19. *Liu, H., et al., Early phase laser induced plasma diagnostics and mass removal during single-pulse laser ablation of silicon. Spectrochimica Acta Part B: Atomic Spectroscopy, 1999.* ***54****(11): p. 1607-1624.*

20. *Lee, Y.T. and R. More, An electron conductivity model for dense plasmas. Physics of Fluids (1958-1988), 1984.* ***27****(5): p. 1273-1286.*

21. *Ho, J., C. Grigoropoulos, and J. Humphrey, Computational study of heat transfer and gas dynamics in the pulsed laser evaporation of metals. Journal of Applied Physics, 1995.* ***78****(7): p. 4696-4709.*

22. *Aragón, C., F. Peñalba, and J. Aguilera, Curves of growth of neutral atom and ion lines emitted by a laser induced plasma. Spectrochimica Acta Part B: Atomic Spectroscopy, 2005.* ***60****(7): p. 879-887.*

23. *Detalle, V., et al., An evaluation of a commercial Echelle spectrometer with intensified charge-coupled device detector for materials analysis by laser-induced plasma spectroscopy. Spectrochimica Acta Part B: Atomic Spectroscopy, 2001.* ***56****(6): p. 1011-1025.*

24. *Kumar, V. and R. Thareja, Studies of excimer-laser-produced copper plasma in the presence of background gas. Journal of Applied Physics, 1990.* ***67****(7): p. 3260-3263.*

25. *Dreyfus, R., Cu0, Cu+, and Cu2 from excimer-ablated copper. Journal of applied physics, 1991.* ***69****(3): p. 1721-1729.*

26. *Lee, Y.-I., et al., Interaction of a laser beam with metals. Part II: Space-resolved studies of laser-ablated plasma emission. Applied spectroscopy, 1992.* ***46****(3): p. 436-441.*

27. *Kramida, A., et al. NIST Atomic Spectra Database (version 5.2), [Online]. Available: http://physics.nist.gov/asd [Sat Jan 28 2015]. National Institute of Standards and Technology, Gaithersburg, MD. 2015.*

28. *Griem, H.R., Principles of plasma spectroscopy. Vol. 2. 2005: Cambridge University Press.*

29. *Lu, Y.-F., Z.-B. Tao, and M.-H. Hong, Characteristics of excimer laser induced plasma from an aluminum target by spectroscopic study. Japanese journal of applied physics, 1999.* ***38****(5R): p. 2958.*

30. *Atwee, T., L. Aschke, and H. Kunze, Investigations of laser-produced plasmas from boron nitride targets. Journal of Physics D: Applied Physics, 2000.* ***33****(18): p. 2263.*

31. *Vijayan, T. and V. Rohatgi, Characteristics of exploding-wire plasmas. Plasma Science, IEEE Transactions on, 1985.* ***13****(4): p. 197-201.*

32. *Bekefi, G., Principles of laser plasmas. New York, Wiley-Interscience, 1976. 712 p, 1976.* ***1****.*

33. *El-Astal, A. and T. Morrow, Wavelength dependent refractive effects and Stark broadening in laser-induced YBa2Cu3Ox plasma plumes. Journal of applied physics, 1996.* ***80****(2): p. 1156-1160.*

34. *Liu, H., et al., Nonlinear changes in plasma and crater properties during laser ablation of Si. Applied physics letters, 1999.* ***75****(9): p. 1216.*

35. *Deeney, C., et al., Role of the implosion kinetic energy in determining the kilovolt X-ray emission from aluminum-wire-array implosions. Physical Review A, 1991.* ***44****(10): p. 6762.*

36. *Yunlian, Q., et al., Electron beam welding, laser beam welding and gas tungsten arc welding of titanium sheet. Materials Science and Engineering: A, 2000.* ***280****(1): p. 177-181.*

37. *Konjevic, N. and W. Wiese, Experimental Stark widths and shifts for spectral lines of neutral and ionized atoms. Journal of physical and chemical reference data, 1990.* ***19****(6): p. 1307-1385.*

38. *McWhirter, R., Spectral intensities, in Plasma diagnostic techniques. 1965. p. 201.*

39. *David A. Cremers, L.J.R., Handbook of laser induced breakdown spectroscopy. 2006: New York: Wiley.*